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STUDY ON VARIOUS ELEMENTS OF THE GEOSCIENCES
WITH RESPECT TO SPACE TECHNOLOGY

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FINAL REPORT**TABLE OF CONTENTS****A. INTRODUCTION**

- (1) Purpose and Strategy of the Study
- (2) Organization of the Report

B. SUMMARY FINDINGS**C. BASIS FOR A NASA PROGRAM IN GEOSCIENCE AND APPLICATIONS**

- (1) U.S. Needs and Global Outlook for Non-Renewable Resources
- (2) Global needs and Outlook for Civil Works Development
- (3) Importance of Global Geoscience Studies of the Planet Earth
- (4) Rationale and Purpose of a Geoscience and Applications Program
- (5) Information Requirements for the Study of the Earth as a Planet

D. PROPOSED TEN YEAR PLAN FOR A NASA PROGRAM IN NON-RENEWABLE RESOURCE APPLICATIONS OF SPACE TECHNOLOGY

- (1) Preface
- (2) Purpose of the Non-Renewable Resources Program
- (3) Program Goals
- (4) Program Objectives
- (5) Program Organization

**Appendix I - Current Status of Geological Remote Sensing
Techniques**

A. INTRODUCTION

(1) Purpose and Strategy of the Study

The purpose of this study was: (i) to examine the relationships between space technology and various elements of the geosciences, and (ii) to evaluate the utility of space acquired data for both basic and applied studies of the geology of the earth. This study was largely conceptual in nature, focusing upon the gaps in our current ability to make effective use of remote sensing technology within the earth sciences. The overall goal was to formulate a long range plan for future research that involved an appropriate balance between the development and application of space techniques within the geological sciences.

In addressing these broadly stated objectives, a detailed review of the current measurement capabilities of both aerial and orbital remote sensing systems was conducted. This review was concerned with identifying the various types of geological information that can be obtained through the analysis of remote sensing data. Future technological advances that would result in improved measurement capabilities were also considered, and the geological utility of these future sensor systems was explored as well.

The review of technological capabilities spanned a wide variety

of remote sensing techniques, ranging from electromagnetic remote sensing methods (e.g. visible - infrared - microwave imaging systems) to potential field measurement techniques (e.g. gravity and magnetic field surveys). The relative maturity of individual technique areas was evaluated, and the current pace of R&D within individual areas was assessed. This review was not an end in itself, however. A major effort has been made in the course of the study to maintain a broad perspective in determining the appropriate nature and scope of future R&D in geologic remote sensing, and to avoid focusing upon sensor system technology.

In parallel with these technological aspects of the project, a complementary effort was made to evaluate the potential utility of space measurements for both applied and basic geological investigations. National needs for global information on non-renewable resources have become increasingly apparent during the past year, largely through the Non-Fuel Minerals Policy Review conducted during the Carter administration and the Congressional hearings leading to the passage of the National Materials and Minerals Policy, Research, and Development Act of 1980. These federal policy making activities have highlighted the need for the development of advanced technology that can potentially be applied to practical problems associated with resource evaluation and development.

At the same time, the scientific benefits of global planetary studies have become increasingly apparent as a consequence of the

aggressive program of planetary exploration conducted by the United States during the past two decades. Preliminary studies of the surface geology and interior structure of the other terrestrial planets have raised intriguing questions about the nature and evolution of the earth. Many of these questions can only be answered through the use of the same types of space technological systems that have provided a globally comprehensive, synoptic view of other planetary bodies. The potential scientific benefits of space technology for studying the geology of the earth have been articulated in a series of meetings recently held by the Committee on Earth Sciences of the National Academy of Science.

In formulating a long term plan for future research in geologic remote sensing, the unique types of geological information that be obtained through the analysis of space acquired data were examined in relation to the national needs and scientific requirements described above. This plan seeks to strike a balance between the development of remote sensing methods and the experimental application of these methods to both scientific and practical geological problems.

(2) Organization of the Final Report

Section B of this report presents the summary findings of the project with regard to the utility of currently available space technology for geological investigations. (A graphical summary

of current measurement capabilities is contained in Appendix I.) Section C describes potential applications of space derived information in relation to national needs for global resource information and major scientific questions pertaining to the geology of the earth's crust. Section D presents a proposed plan for a long term, NASA sponsored program in geological remote sensing research and development.

B. SUMMARY FINDINGS

A review of current research activities and past research accomplishments in the field of geological remote sensing was conducted during the course of this study. This review revealed certain limitations in the scope of ongoing R&D which need to be overcome in the future in order to make full and effective use of space acquired data.

A discussion of the findings of this study can best be made with reference to Figure 1, which summarizes remote sensing techniques currently under development and the various types of geological information commonly employed in geologic mapping and crustal studies. Space remote sensing methods of geological relevance can generally be classified as electromagnetic techniques which are designed to measure electromagnetic radiation reflected or emitted from the earth's surface, and potential field methods which involve the measurement of the earth's gravity and magnetic fields. Past work on electromagnetic methods has concentrated upon those techniques that operate in the visible, near infrared and shortwave infrared (0.4-2.5 micrometer wavelengths), the thermal infrared (primarily 8-14 micrometer wavelengths), and the microwave (1-50 centimeter wavelengths) portions of the electromagnetic spectrum. Potential field methods involve measurements of the total strength (scalar magnitude) and directional characteristics (vector components) of the earth's magnetic and gravity fields at orbital elevations.

RELATIONSHIPS BETWEEN REMOTE SENSING TECHNIQUES AND GEOLOGICAL INFORMATION COMMONLY EMPLOYED IN GEOLOGIC MAPPING AND MODEL DEVELOPMENT

REMOTE SENSING TECHNIQUES					
GEOLOGICAL INFORMATION	ELECTROMAGNETIC			POTENTIAL FIELD	
	VISIBLE/ NEAR IR	THERMAL INFRARED	MICROWAVE	MAGNETIC FIELD	GRAVITY FIELD
	◆	◆	◆	◆	◆
	◆	◆	◆		
	◆	◇	◆		
	◇	◇	◇	◆	◆
ROCK TYPE					
GEOBOTANICAL CORRELATIONS					
SURFACE TOPOGRAPHY					
SUBSURFACE STRUCTURE					

- ◆ PRIMARY RELATIONSHIP
- ◇ SECONDARY RELATIONSHIP

Figure 1

Geologists analyze the various types of data collected by these measurement techniques and make inferences about the structure, composition, and distribution of crustal materials. Geologists are specifically interested in obtaining information about the mineralogy and lithology of crustal materials. This type of information is easily accessible in areas where rocks and rock weathering products are exposed at the earth's surface. In heavily vegetated regions, the composition of underlying rock materials can be inferred under certain circumstances on the basis of the distribution, morphology, and chlorophyll composition of vegetative species. Past research has indicated that various geobotanical correlations could potentially be applied to geological mapping in both tropical and temperate regions.

In addition to information on rock composition, geologists employ topographic data to characterize and analyze the morphology of the earth's surface. Boundaries between different morphological units in many cases correspond to lithologic boundaries between different rock units, or to major structural discontinuities within the crust. Accurate knowledge of surface topography is also essential in using remote sensing data for compositional mapping, since the grade and azimuthal direction of natural slopes can significantly influence measurements of surface reflectance and/or emissivity averaged over large areas (i.e. 100 square meters or greater).

Geologists synthesize information about the near surface composition and structure of the crust and then commonly extrapolate this information into the subsurface. Various models of subsurface characteristics can be developed, and these models are constrained by knowledge of surficial conditions and near-surface measurements of various geophysical parameters (e.g. gravity and magnetic fields, heat flow, seismicity, etc.). Potential field measurements in many cases place critical constraints on models of subsurface structure and composition.

As shown in Figure 1, electromagnetic remote sensing methods are primarily useful for obtaining information about near surface geology, whereas potential field techniques are more useful for obtaining insight into the subsurface geology of the crust. Review of past R&D accomplishments within the context of the technique - information matrix presented in Figure 1 formed the basis for the major findings of this study project. These findings were as follows:

There currently exist serious limitations in our ability to make effective use of space derived geological information. The sophistication of remote sensing techniques has increased enormously over the past decade. Multispectral imaging in the visible/near infrared/shortwave infrared region has been shown to be useful for discriminating certain types of iron oxides and clay minerals that are commonly associated with hydrothermal min-

eral deposits. Multispectral imaging at thermal infrared wavelengths has been shown to be useful for discriminating silicate and carbonate rocks, and, in addition, for differentiating silicate rocks on the basis of their free silica content. Other successful accomplishments have occurred in other technique areas. In many instances, the types of geological information derived from remote sensing measurements is fundamentally different from the types of information that are commonly obtained by ground based field mapping and conventional sample analysis.

Space derived information is potentially applicable to a broad range of geological investigations, such as resource evaluation and development, subsurface disposal of hazardous wastes, site selection for critical facilities (e.g. nuclear power plants, defense installations, etc.), and forecasting geological hazards (e.g. earthquakes and landslides). The ability to arrive at practical decisions on any of these matters is based upon the compilation and synthesis of pertinent information for the case under consideration, and use of geological models which largely reflect past experience in dealing with a generic type of problem.

Geological models serve a variety of purposes. Certain types of models describe the geological settings in which specific types of mineral deposits commonly occur. Others describe the general structure of the earth's crust in terms of compositional boundaries, physical properties, thermal structure, etc. Still

others describe regional stress conditions and mechanism for relieving accumulated tectonic stress. The majority of existing models make use of classical types of geological information that have been acquired by conventional measurement techniques. In most instances, existing models are not designed nor are they readily adaptable to the types of geological information that can be obtained through the analysis of space acquired data

One of the major, unexpected findings of the present study was that currently available geological models place far greater restrictions on our ability to apply remote sensing techniques to 'real world' problems, than do the present day measurement capabilities of remote sensing systems. This problem can only be overcome through an expanded program of model development which seeks to understand the significance of space derived geological information for specific applications.

Existing remote sensing methods and those currently under development are not being fully exploited for geological mapping and crustal modeling. Examination of the current scope of R&D efforts in relation to the technique - information matrix (Figure 1) described above reveals that certain applications of existing remote sensing methods are not being adequately explored at the present time. Past research has concentrated almost exclusively on two elements of this matrix (see elements labelled "proven utility" in Figure 2). A great deal of historical research has been conducted in developing photogrammetric

TECHNIQUE DEVELOPMENT FOR GEOLOGICAL MAPPING AND MODELING

REMOTE SENSING TECHNIQUES						
ELECTROMAGNETIC				POTENTIAL FIELD		
		VISIBLE/ NEAR IR	THERMAL INFRARED	MICROWAVE	MAGNETIC FIELD	GRAVITY FIELD
ROCK TYPE						
GEOBOTANICAL CORRELATIONS						
SURFACE TOPOGRAPHY						
SUBSURFACE STRUCTURE						

PRIMARY RELATIONSHIP
 SECONDARY RELATIONSHIP

PROVEN UTILITY
 SHOWS PROMISE

Figure 2

techniques to obtain topographic information through the analysis of panchromatic, stereoscopic imagery. Furthermore, since the advent of electromechanical imaging systems and orbital measurement platforms, a major research effort has been devoted to the use of visible and near infrared techniques for discriminating different types of rock materials. However, many of the other elements of the technique - information matrix have received very little attention in the past.

Promising experimental results have been obtained in the use of thermal infrared techniques for rock type discrimination, the use of microwave methods for topographic analysis and structural mapping, the use of orbital magnetic field measurements for subsurface crustal modeling, and in the use of visible/near infrared techniques for geobotanical mapping. However, these experimental indications of potential applicability are based upon the study of a very limited group of test sites, which, in many cases, were chosen because of their anticipated suitability for the application of a particular technique. Clearly, a great deal of additional experimentation in more complicated environments is required to truly assess the global applicability of these techniques in obtaining the kinds of geological information described above.

Finally, significant segments of the technique - information matrix have been almost totally overlooked in the past (see unshaded elements where a primary relationship is indicated in

Figure 2). These overlooked areas involve the use of thermal infrared and microwave techniques for geobotanical mapping, and the use of calibrated measurements of radar backscatter for purposes of rock type discrimination.

New methods are needed for analyzing remote sensing data in combination with data acquired by conventional measurement techniques. Geological remote sensing should never be viewed as an end in itself. It is one of many tools that geologists use to gain greater insight into the character of the earth's crust. In most cases, orbital remote sensing systems collect data at scales and precisions that are not comparable to ground based and aerial surveys. Moreover, the very nature of space derived information may differ in a fundamental manner from information obtained through the analysis of conventional geological data (e.g. consider the comparison between an orbital measurement of average spectral reflectance over a 30m x 30 m area given in units of watts per square centimeter - steradian and a ground based 'point measurement' of heat flow given in units of watts per square centimeter). New methods specifically are required for combined analysis of orbital imaging data and orbital potential field data for purposes of developing improved three dimensional models of crustal structure and composition. At the same time, new methods of integrating conventional types of data and information into the analysis and interpretation of remote sensing data are necessary.

These new methods of data analysis should be specifically concerned with procedures for formatting and displaying different data types, methods of compressing, restoring, and physically manipulating large data sets, protocols for maintaining the integrity of individual data sets, and procedures for conducting statistical pattern recognition analyses of data collected at different resolutions and accuracies. The need to maintain careful distinctions between physical measurements, data (i.e. reduced measurements), and information (i.e. interpreted data) will become increasingly important as diverse collections of measurements, data, and information are computer processed and mathematically manipulated.

Development of geologic remote sensing methods is not keeping pace with current advances in technological capabilities. There are a variety of evolving technologies which could potentially be adapted for use in geologic remote sensing. Examples include the use of solid state detector arrays for narrowband multispectral imaging at visible and infrared wavelengths, the use of laser technology for digital topographic mapping and multispectral imaging, the use of large space structures for electromagnetic sounding at long (meter-sized) wavelengths, and the use of phased array radar systems that would provide highly flexible beam pointing and steering capabilities. These various technologies are sufficiently well developed at the present time to warrant careful evaluation of their potential utility for geological applications. Review of current R&D activities indicated,

however, that relatively limited efforts were currently under way
o explore how the measurement capabilities provided by these
advanced technologies could potentially contribute to geological
remote sensing capabilities.

The community of researchers involved in the experimental testing
and application of geological remote sensing techniques needs to
be broadened and expanded. The group of scientific investigators
currently involved in remote sensing research has been highly
creative and productive in the past. However, this group, by
itself, is numerically too small and scientifically too narrowly
focused to attack the broad range of research problems and
technological challenges described above. The future success of
geologic remote sensing will be directly dependent upon the size
and caliber of the research community involved in this high
interdisciplinary field. Every effort should be made through the
normal channels of scientific communication and the process of
awarding grants, contracts, fellowships, and scholarships to
expand this community. These efforts can be properly viewed as a
long lead time investment in the successful development and
utilization of space technology for geological applications.

C. BASIS FOR A NASA PROGRAM IN GEOSCIENCE AND APPLICATIONS

(1) U.S. Needs and Global Outlook for Non-Renewable Resources

The U. S. currently possesses the largest national economy in the world, measured in terms of Gross National Product (GNP). The U. S. economy consumes enormous quantities of mineral resources and fossil fuels on a yearly basis. Energy and processed materials of mineral origin accounted for approximately one-fifth of the U. S. GNP in 1975 (Mineral Facts and Problems, 1975).

Total U. S. Consumption of non-renewable mineral resources and fossil fuels has increased annually during the last three decades. During the remainder of the twentieth century, domestic demand for metallic mineral commodities is expected to increase at a rate of a few percent per year. This demand growth rate is roughly comparable to the forecasted rate of U. S. population growth during the next twenty years, indicating that per capita consumption of metallic commodities will remain roughly constant within the foreseeable future.

The U. S. obtains mineral commodities from three sources:

(i) primary production from domestic mines, (ii) secondary recovery of scrap material, and (iii) imports from foreign countries.

Primary domestic production cannot meet U. S. demand for many minerals at current world market prices. The dollar value of most mineral commodities is expected to increase during the coming years and it will become economically feasible to mine lower grade mineral deposits. There is a widespread misconception that domestic production from known, low grade reserve deposits may account for a larger share of U. S. consumption under these circumstances. However, the

low grade margins of many known deposits do not contain increasingly larger quantities of recoverable metal or fuel. Tonnage - grade relationships for many deposits indicate that recoverable reserves decrease with decreasing ore grade. In addition, energy costs involved in mining and milling lower grade ores increase exponentially as the bulk metal concentration decreases. These considerations strongly suggest that domestic mineral production from known deposits will not supply a significantly larger fraction of future U. S. demand.

As the value of raw materials increases, there is a greater economic incentive to recover the mineral resources contained within scrap material. Secondary recovery presently supplies an appreciable fraction of U. S. demand for major metals. Under current economic conditions, the rate at which a metal is recycled to meet demand requirements depends largely upon the service lifetimes of various manufactured products. Elements such as iron, nickel, lead, copper and aluminum are used in a wide variety of products, and the total tonnage of these metals in manufactured form is quite large. Scrap recycling currently accounts for one-quarter to one-half of U. S. needs for iron, nickel, and lead. The extent to which recycling can satisfy domestic demand for major metals over the long term is currently the subject of debate.

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Secondary recovery is not a major source of many minor metals. Elements such as titanium, tungsten, cobalt, manganese, vanadium, niobium, and tantalum are used to produce steel alloys with unique thermal, electrical, and mechanical properties. These steel alloys have very specific usages within the aerospace, electronics, and construction industries. The total tonnage of minor metals contained within manufactured products is comparatively small. Furthermore, the service lifetimes of manufactured goods such as jet engines and computer components are significantly longer than those of automobiles and beverage containers. It is unlikely that recycling will be able to supply a significant fraction of future U. S. demand for minor metals. In addition, secondary recovery procedures are not applicable to several key non-metallic resources such as uranium and fossil fuels used in energy production, and nitrates and phosphates used in making fertilizers.

Domestic production and secondary recovery have not been able to keep pace with steadily increasing U. S. demand for many mineral resources. Consequently, the U. S. has become increasingly dependent upon foreign countries for its supplies of needed raw materials. The U. S. currently imports more than ninety percent of its requirements for manganese, chromium, titanium, cobalt, niobium, and strontium, and more than half of its requirements for aluminum, tin, zinc, nickel, tungsten, and platinum. Global consumption of non-renewable mineral

resources is expected to increase at a rate exceeding the demand growth rate of industrialized nations, as less developed countries strive to achieve higher standards of living for their citizens. Therefore, the U. S. will encounter greater competition on the world market in the future and the value of many mineral commodities (measured in constant dollars) will continue to increase.

These considerations indicate that the U. S. is faced with a serious resource supply problem during the remainder of the twentieth century. Our national economy is becoming increasingly reliant upon foreign imports of necessary mineral resources. These commodities are becoming increasingly costly, and, in some instances, are of uncertain availability. The Congress of the United States has recognized the problem and has enacted the Mining and Minerals Policy Act of 1970 to promote and monitor resource exploration activities. It is necessary that the U. S. have access to a stable supply of raw materials which can be purchased at an equitable price. This goal can be met by continued domestic exploration and by maintaining a diversified group of foreign suppliers.

There has been an extensive search for mineral resources within the U. S. during the last hundred years. Geological mapping and geophysical measurements have been performed over large areas of potential mineralization. Deposits which can be readily identified on the basis of surface rock outcrops, structural features, or geochemical alteration patterns have been largely discovered. Major mineral deposits remaining to be discovered are likely to occur at depth and be obscured by overlying rock formations. In order to locate these as

yet undiscovered resources, it is necessary to develop more sophisticated methods for mineral exploration.

Exploration methodology can be specifically improved in two ways. Firstly, we need to develop a better understanding of the crustal processes responsible for the formation, deformation, and alteration of mineral deposits. It is particularly important to develop more sophisticated models of mineral emplacement since these models provide a framework for interpreting geophysical measurements. Secondly, we need to develop a better understanding of surface phenomena that are associated with subsurface mineral deposits. Surface weathering of the exposed margins of a buried deposit, or percolation of groundwater through a completely buried deposit can produce distinctive geochemical patterns on the ground surface. The surface expression of these patterns may be distorted by subsurface crustal structures such as faults and folds, and by variations in surface topography. Furthermore, geochemical anomaly patterns may be correlated with areal variations in vegetative cover within certain types of ecological environments.

Aerospace technology can contribute to the effectiveness of resource exploration activities by assisting in the development of more sophisticated exploration methods. Space-acquired measurements of electromagnetic radiator reflected and/or emitted from the earth's surface provide information concerning the physical properties of surficial materials. Space-acquired measurements of the earth's geopotential fields provide information about subsurface crustal structure which is useful in interpreting surface property measurements. Space-acquired data can be used to investigate subtle regional variations in structural patterns or surface composition which are directly related to

the emplacement or alteration of subsurface mineral deposits. Regional measurements of surface composition, ground moisture, vegetative cover, and surface topography can be obtained in a comprehensive and timely manner by orbiting sensor platforms. These measurements can be acquired in regions of known mineralization and can subsequently be used in developing models of ore body formation. This type of data needs to be collected on a global scale in order to investigate the formation of different types of deposits. For example, uranium-bearing mineralization of economic importance exists in four different types of occurrences: within quartz pebble conglomerates, porous sandstones, granitic rocks, and as replacement deposits in surficial materials. Space acquired data can also be used to examine geochemical patterns and vegetative patterns in the vicinity of known mineral deposits. These types of studies would provide valuable information in identifying regions of potential mineralization.

Aerospace technology can also improve the efficiency of resource exploration activities. This is particularly true in the case of foreign projects in areas which have not been extensively explored in the past. Space-acquired measurements can provide basic knowledge of surface topography and regional drainage patterns in areas which have not been previously photographed by aerial surveys. Measurements of surface composition, soil moisture, and vegetative cover can also be used in devising a regional exploration strategy. This type of information is extremely useful in planning reconnaissance mapping and sampling investigations and in choosing areas for geophysical measurements. Increased efficiency would reduce the time and money required to conduct a large scale exploration project, particularly in remote areas.

In summary, space technology can improve both the effectiveness and the efficiency of resource exploration activities conducted within the U. S. and abroad. Increased effectiveness of domestic exploration should serve to bolster U. S. mineral reserves and offset the trend of growing dependence upon imported mineral commodities. Increased effectiveness and efficiency of resource exploration on a global scale should ensure that mineral supplies can be obtained from a diverse group of foreign countries in the future. These improvements will also result in a net savings in the time and money required to explore and develop a mineral property. Application of space technology to resource exploration and assessment problems thus provides one means of assisting the U. S. in meeting its needs for non-renewable resources during the remainder of the twentieth century.

(2) Global Needs and Outlook for Civil Works Development

Worldwide demand for raw materials and manufactured goods will increase throughout the remainder of this century as the result of the continued growth of the Earth's population (currently increasing at two percent annually). In order to meet this demand, resource exploration activities are being conducted in increasingly remote regions such as the Arctic Ocean. The development of extraction facilities and transportation systems in these regions will necessitate civil works projects of unprecedented size and complexity. The recently completed Alaskan oil pipeline is an excellent example of this type of large scale engineering project. Global needs for food, clothing, shelter, and energy will also require civil works development to expand production and distribution facilities and provide housing.

Over the course of the past two decades, there has been a significant increase in both national and international concern over the care and preservation of the Earth's environment. Future civil works projects will require more careful and comprehensive planning as the result of this increased environmental awareness. In particular, these projects may need to consider regional watershed drainage systems and wildlife migratory habits in addition to more

traditional factors such as foundation strength and stability. Furthermore, relevant types of hydrological, ecological, and geological data must be obtainable on a timely basis so as not to delay the development of necessary civil works projects. This is particularly true in the case of energy related projects such as surface coal mining, oil refinery and pipeline construction, and nuclear reactor site selection. Research and development activities which provide pertinent engineering data on regional and global scales can directly assist the planning and organization of future civil works development projects.

(3) Importance of Global Geoscience Studies of the Planet Earth

Exploration of the solar system has proceeded at a greatly increased pace with the advent of satellite and spacecraft technology. Orbiting sensor platforms have been used to photograph planetary surfaces, map regional variations in surface composition, and measure the gravity and magnetic fields associated with different planetary bodies. Probe spacecraft have determined the chemical composition, temperature, and density of planetary atmospheres. Lander spacecraft have evaluated the mechanical properties of surficial material and performed bulk compositional analysis of soil and rocks. Manned missions to the moon sampled lunar material and conducted in situ measurements of surface gravity, magnetic field strength, and crustal heat flow. In addition, the Apollo astronauts deployed scientific instruments to monitor lunar seismic activity.

Knowledge of the structure and composition of the earth constitutes the fundamental conceptual framework used in interpreting empirical observations and measurements obtained by these various spacecraft missions. For example, the earth is known to consist of a central iron rick core surrounded by a dense, massive mantle and a thin,

low density crust. These principal subdivisions of the earth's interior are commonly invoked in interpreting measurements of surface topography, surface gravity, moment of inertia, and magnetic field strength performed for other planetary bodies. Similarly, studies of terrestrial geological processes associated with tectonic deformation, volcanic activity, and surface erosion provide the necessary conceptual foundation for interpreting surface features observed on other planets in terms of formative geological processes. For example, the basic principles of stratigraphy developed for sedimentation in aqueous and aeolian environments on the earth have been successfully employed in mapping sequences of impact crater ejecta deposits on the moon.

Exploration of the solar system has raised several critical questions about the geological evolution of the earth. Comparative planetary studies indicate that impact cratering had a pervasive influence on early crustal development throughout the inner solar system. Large scale impact cratering events have been found to be responsible for major variations in crustal topography, deep seated fracturing of crustal basement material, and redistribution of near surface crustal material over distances of thousands of kilometers. In fact, impact cratering during early solar system history is inferred to have been sufficiently

intense to produce a surficial layer of comminuted and brecciated material extending to depths of several kilometers of each of the terrestrial planets.

The crusts of the Moon, Mercury, and Mars contain widespread regions of ancient cratered terrain that was intensely bombarded during the first billion years of solar system history. In addition, Mercury displays a globally extensive system of ridges indicative of net crustal compression whereas Mars exhibits a large scale system of linear depressions indicative of net crustal extension. The earth's crust has preserved very little evidence of its early history. Furthermore, the outermost portion of the earth currently consists of a group of interlocking, rigid plates which are in a state of continual, relative motion. Plate motion is inferred to be caused by convective flow within the earth's interior. The beginning phases of plate formation and differential plate motion signaled a critical transition in the tectonic regime controlling the deformation of the earth's crust. In order to truly understand the planetary evolution of the earth it is necessary to know when plate formation occurred, how the primeval crust was fractured and broke up, and why the earth of all the inner solar system planets manifests this unique crustal behavior.

Detailed examination of lunar samples together with photogeological mapping studies and remote sensing surveys has indicated that the exposed crust of the moon consists of two principal rock types. Basement material forming the heavily cratered lunar highlands is chiefly composed of plagioclase rich igneous rocks, whereas the lunar maria consists of basaltic lava flow deposits. This dichotomy in crustal composition also occurs on the earth: continental crust is generally enriched in silica and alumin compared to oceanic crust which contains relatively greater proportions of iron and magnesium. The compositional similarity between lunar and terrestrial crustal material is surprising in view of the very different set of tectonic processes operating upon the two bodies. Furthermore, preliminary investigations of Mars indicate that the dichotomy between older, sialic crustal materials and younger, mafic volcanic deposits may also exist on that planet.

These comparative planetary studies raise several questions about the constitution of the earth, namely: Do portions of the continental crust represent reworked segments of the primeval crust which formed immediately after the accretion of the earth? If so, do these recycled materials provide any evidence concerning early crustal composition, ancient volcanic activity, or the existence of a primitive magnetic

field? Furthermore, is oceanic crust continuously transformed into continental crustal material by some geochemical refining process in the vicinity of converging plate boundaries? If such a process has occurred in the past, have economically important elements such as iron, magnesium, nickel, and copper been concentrated within sections of the continental crust?

The foregoing discussion illustrates that parallel investigations of the earth and other planetary bodies can substantially benefit from increased and improved interaction. A global view of the structural and geochemical characteristics of other planetary surfaces has raised many questions concerning the structure and constitution of the earth. At the same time, detailed studies of geological processes operating on the earth supply essential information needed to interpret observations and measurements conducted for other planetary bodies. Geoscience studies employing aerospace technology can improve our basic understanding of the geological evolution of the planet earth by obtaining global measurements of crustal structure and composition and the earth's geopotential fields. This knowledge will serve to expand the interpretive framework in which we view the other planets. Consequently, the basic research performed under the Geoscience Program will permit scientific investigators to exploit the data base compiled for other planetary bodies more fully and more effectively.

(4) Rationale and Purpose of a Geoscience and Applications Program

The United States is one of the most prosperous nations in the world and its citizens enjoy a comparatively high standard of living. At the present time, there is widespread national concern that the quality of life within the United States is declining due to inflationary pressures being exerted upon our economy and degradation of the natural environment in which we live. Among the critical problems confronting our nation are the need to obtain the raw materials required for the operation and growth of the United States' economy and the need to plan for domestic development in a manner that ensures the safety of individuals and the integrity of the environment.

The purpose of NASA's Geoscience and Applications Program is to develop aerospace technology and conduct geoscience studies which assist in solving problems of national scope and expand basic knowledge about the solid earth. Spaceborne sensors and imaging systems can measure a variety of parameters which provide information about the composition and structure of the earth's crust. Space acquired data provides information at a unique synoptic scale that can reveal subtle variations in surface chemistry, structural fabric, and vegetative cover which are not readily apparent in airborne

surveys performed at much lower altitudes. Similarly, measurements of the earth's gravity and magnetic fields obtained at orbital altitudes supply unique information about subsurface crustal structure at a regional scale. There is no practical means of performing these types of geophysical measurements on a global basis using currently available airborne instrumentation.

The United States Congress has recently established priority goals for national research and development activities in enacting the National Science and Technology Policy, Organization, and Priorities Act of 1976. This legislation specifically declares that the United States' science and technology should contribute to the following goals: fostering human well-being; assuring an adequate supply of food, materials, and energy for the nation's needs; and preserving a healthful and esthetic natural environment. Geoscience information obtained by aerospace technology is directly applicable to these goals in the context of three specific problem areas: (1) resource exploration and assessment, (2) civil works development, and (3) natural hazards forecasting. Geoscience information is required in prospecting for new deposits of mineral resources, planning civil works projects in an environmentally sound manner, and assessing risks associated with such natural hazards as earthquakes, landslides, and volcanic eruptions. The

National Science and Technology Policy, Organization, and Priorities Act also recognizes the importance of enlarging the contributions of American scientists and engineers to the knowledge of man and his universe. Global studies of the composition and structure of the earth employing aerospace technology will improve our understanding of the dynamic geological processes that are responsible for the evolution of the earth as a Planet. Therefore, the purposes of NASA's Geoscience and Applications Program, namely to assist in solving problems of national scope and to expand basic knowledge about the solid earth, directly address the science and technology goals mandated by the United States Congress.

NASA has the official responsibility to further the development of aerospace science and technology on a national level. Over the course of the past two decades, NASA has demonstrated a high degree of competence in planning and organizing complex research and technology development programs. The agency is currently participating in and coordinating a variety of consortium projects involving federal agencies, academic investigators, and industrial scientists from the United States and abroad. The history of the Lunar and Planetary Programs indicate that NASA has the ability to attract geoscientists of the highest caliber to serve as principal

investigators and as members of advisory committees and peer review panels. The agency has prior experience in conducting terrestrial research programs in connection with the study of the earth's atmosphere and investigation of earth geodynamics. In addition, it has exhibited a strong commitment to the dissemination of space acquired data and related research results to the widest possible community of scientific users.

In view of its administrative competence and proven expertise, NASA is the logical agency to assume a lead role in coordinating global geoscience studies. No other federal department or agency is in a position to develop advanced aerospace measurement techniques which are applicable to global geoscience problems, nor is there a private sector organization with the diverse expertise needed to conduct global geoscience investigations.

NASA's role is pursuing geoscience studies related to national needs will be to perform research and development activities leading to the design of sensor systems and data management facilities that are optimized for geoscience users. Research performed under NASA auspices will be concerned with the collection, synthesis, and analysis of data which is potentially applicable to problems of resource exploration, civil works development, and natural hazards assessment. Space acquired data may be used in making a variety of public and

private decisions. However, NASA itself will not participate in resource exploration ventures or civil works projects nor will it assess risks associated with potential natural hazards.

The Geoscience and Applications Program described in this document is designed to develop aerospace technologies and geological models that can ultimately be used in discovering mineral resources, planning civil works projects, and evaluating natural hazards. In addition, research conducted under this program will materially contribute to our understanding of the earth as a dynamic, evolving planetary body. Space technology can directly improve the efficiency and effectiveness of resource exploration activities. It can also aid in assessing the environmental impact of civil works projects and in evaluating the risks posed by natural hazards. These benefits contribute to national United States goals concerning long-term supply of raw materials and environmental protection. They also serve traditional foreign policy objectives to promote the welfare of all mankind and to protect our global environment.

(5) Information Requirements for the Study of the Earth as a Planet

The information requirements for the study of the earth as a planet can be broadly classified into four topical problem areas. These problem areas are interrelated. Therefore, the data records and map products discussed under each specific problem area are generally applicable to investigations within the other areas as well.

1. Crustal composition. Global geologic maps are required in order to investigate areal variations in crustal composition on local, regional, continental, and global scales. Geological maps delineate the boundaries of rock formations which outcrop on or near the earth's surface. Rock formations are differentiated from one another on the basis of lithological characteristics which are generally determined by the rock's bulk composition and the geological environment in which it was formed (e.g., igneous, metamorphic, or sedimentary). Time-stratigraphic relationships between different rock formations can commonly be established on the basis of outcrop patterns and inferred subsurface structure. These stratigraphic relationships provide information about temporal variations in crustal composition on regional, continental, and global scales.

2. Crustal structure. Global tectonic maps are required in order to investigate structural boundaries between various segments of the earth's crust on local, regional, continental, and global scales. Tectonic maps delineate fractures and faults within crustal materials and also depict crustal folds using accessory stratigraphic data. Cross cutting relationships between systems of faults and fractures can be used together with geological maps to model the deformation history of a particular crustal segment. Tectonic maps also provide information used in modeling the subsurface configuration of rock formations which outcrop at the earth's surface.

3. Dynamic crustal processes. The morphology of the earth's surface is currently being modified by four principal geological processes: tectonism, volcanism, erosion, and sedimentation. In order to understand the manner in which these processes operate on regional and planetary scales, it is necessary to construct relevant physical models and test these models against empirical observations. Information required for the construction of physically meaningful models includes: (i) records of relative movement and internal deformation of tectonic plates, (ii) records of surface volcanic activity and the volumetric output of individual volcanic eruptions, and (iii) global topographic maps. Tectonic and volcanic processes occurring near the earth's surface are intimately

interrelated. Consequently, measurements of tectonic deformation rates are relevant to studies of surface volcanism. For example, records of plate motion at diverging plate boundaries place constraints on models of magma supply at crustal spreading centers. Global topographic maps can be used to perform quantitative geomorphological analyses of landform degradation within different types of erosional environments. Topographic maps can also be employed in conjunction with geologic maps to determine the volumetric significance of different rock types in regions of recent volcanic activity or recent sedimentation. Quantitative models of crustal processes require ancillary information concerning deep crustal structure, volatile transport through the crust, and surface climatic conditions.

4. Internal constitution and dynamics. Global maps of the earth's gravity and magnetic fields are required in order to investigate radial variations in interior earth structure on regional and global scales. Geopotential field maps can be used to infer the position of internal structural discontinuities such as the crust-mantle boundary, the lithosphere-asthenosphere boundary, and the core-mantle boundary. These maps also provide information about lateral variations in the position of the boundaries. Repetitive

maps of the gravity and magnetic fields are needed to investigate dynamic interior processes. Repetitive geopotential field measurements supply information about transient changes in field strength and vector direction which constrain models of core dynamo circulation, mantle convection, and crustal warping. Quantitative models of internal structure and processes require ancillary information concerning seismic activity, heat flow, and the physical properties of geological materials at high temperatures and pressures.

**D. PROPOSED TEN YEAR PLAN FOR A NASA PROGRAM IN NON-RENEWABLE
RESOURCE APPLICATIONS OF SPACE TECHNOLOGY**

1.0 PREFACE

The purpose of this document is to define the conceptual structure and future direction of NASA's Non-Renewable Resources Program. This document describes the goals and objectives of the Program. It also discusses the scope of future programmatic activities in general terms. The Program Plan will be supplemented by various implementation plans that specifically describe the series of tasks to be conducted in support of stated programmatic objectives. Implementation plans for individual program elements are currently being developed at various NASA field centers.

The audience for this document is quite diverse. The Program Plan has been primarily prepared for the use of the NASA management. However it will also be examined by a wide variety of individuals from both inside and outside of NASA, including individual administrators from other government agencies, members of the mineral and petroleum industries, and academic researchers with specialized backgrounds in geology and geophysics.

2.0

PURPOSE OF THE NON-RENEWABLE RESOURCES PROGRAM

The purpose of NASA's Non-Renewable Resources Program is to develop space techniques and methods to improve the effectiveness of global non-renewable resource investigations. Space techniques broadly consist of electro-magnetic remote sensing and potential field measurement techniques which can be developed for use at orbital altitudes. Space methods consist of procedures for analyzing and interpreting space acquired data, together with data acquired by more conventional ground-based and airborne techniques. Space techniques and methods developed by NASA's Office of Space and Terrestrial Applications can be applied to a wide variety of non-renewable resource investigations associated with mineral/hydrocarbon assessment, exploration, and development.

Space techniques and methods are unique in several respects which make them particularly valuable for global non-renewable resource investigations. First, spaceborne remote sensing systems obtain measurements at a synoptic scale that cannot be readily duplicated by remote sensing surveys performed at lower (aircraft) altitudes. Analysis of space acquired data has revealed subtle, regional scale variations in crustal composition and structural fabric that are not readily apparent from aircraft or ground based reconnaissance surveys. There is some evidence to suggest that the occurrence of specific mineral deposits may be correlated with several of these compositional and structural features. The synoptic perspective provided by space methods is also useful for synthesizing, integrating and interpreting geological information derived from conventional methods. Space acquired data permits geologists to extrapolate the results of local, ground based investigations into areas which have not been examined in detail. The ability to synthesize detailed information derived from localized studies is extremely useful in developing comprehensive regional models of crustal structure and composition.

Second, spaceborne remote sensing systems obtain global measurements at a common scale and format. Space systems are designed to obtain physical measurements at a uniform level of accuracy and precision. In contrast, geological information derived from conventional techniques tends to vary enormously in scale, format, and accuracy. Regional analysis of geological conditions in many areas of the world is greatly hindered by the tremendous disparity in the quantity and quality of available information. Space techniques can

provide geologists with useful information at uniform scales, resolutions, and accuracies for reconnaissance mapping on a global scale.

Third, imaging systems mounted on orbital platforms can obtain repetitive measurements over an extended period of time. In this respect they are far superior to traditional aerial reconnaissance surveys which are typically performed during a particular season and time of day. Prior photogeological investigations have demonstrated that subtle structural features are highlighted in aerial imagery by specific solar illumination, snow cover, and vegetative growth conditions that occur during different seasons. Orbital radar systems can also be used to illuminate the earth's surface from different directions at variable angles of incidence. Analysis of aircraft data has shown that multiple sets of radar imagery acquired at different azimuthal and incidence angles provide important information about the physical structure of crustal materials. Comparative analysis of orbital imagery acquired on a repetitive basis can greatly assist photogeologists in identifying subtle structural features and in interpreting the tectonic history of a particular region.

Fourth, earth resources investigations performed by Skylab and the Landsat series of satellites have shown that spacecraft can conduct global remote sensing surveys in a rapid, cost-effective manner. Any attempt to perform comparable remote sensing measurements from aircraft platforms on a global basis would be prohibitively expensive.

Space techniques cannot be used to directly locate mineral/hydrocarbon reserves. Economic concentrations of minerals and hydrocarbons within the earth's crust are identified on the basis of exploratory drilling, laboratory analysis, production testing, development costs, and world market prices for specific commodities. In addition, it is unlikely that space techniques could be used to directly locate mineral/hydrocarbon deposits. Deposits that outcrop at the earth's surface have been largely discovered and exploited in the past. The majority of deposits remaining to be discovered are likely to occur at depth and be obscured by overlying crustal materials. Furthermore, even if minerals of economic significance occurred at the ground surface, it is unlikely that these minerals would be sufficiently abundant or pristine to produce a distinctive spectral signature within data acquired at orbital altitudes.

Space techniques can provide geologists with a wealth of information concerning the composition, structure, and distribution of crustal materials, primarily at a regional scale. Analysis of space data can greatly assist geologists in identifying structural trends and geochemical patterns within the near-surface crust. Geologists use information of this nature together with mineralization models to evaluate the mineral potential of specific areas for purposes of assessment and exploration. Space methods represent powerful tools for performing regional scale geological investigations and for targeting ground based field studies.

In summary, space measurement techniques cannot replace the traditional methods of field investigation that are involved in the search for mineral resources. Space techniques are not a modern panacea for the careful, painstaking, ground based field studies that are required in order to actually discover a new mineral deposit of economic value. However, these techniques do possess unique capabilities that can greatly assist exploration geologists.

3.0 PROGRAM GOALS

3.1 Develop space techniques for systematic evaluation of the geology of the earth's crust for global non-renewable resource investigations

The earth's crust consists of different types of rocks that have been formed primarily by sedimentary and volcanic processes. Rock units may be extensively modified and reworked by metamorphic processes subsequent to their original formation. In addition, tectonism can alter the configuration and physical structure of rock units through folding and faulting processes. Any or all of these geological processes can play a critical role in the emplacement of specific types of mineral deposits.

Geologists involved in the search for mineral resources seek to understand the structure, composition, and evolutionary history of specific portions of the crust. These geologists are typically confronted with such questions as: What type of rocks are present in a particular area? When and how did individual rock units form? Have units been fractured, offset, or otherwise disturbed by crustal motions subsequent to their formation? Can the structural attitude of units exposed at the surface be extrapolated to depth? Have weathering phenomenon altered the composition of rock units near the earth's surface, and if so what is the composition of these units at depth? Have minerals of economic significance formed within a specific section of the crust? If so, where, when, and how were these minerals emplaced? Geologists require information concerning the composition and three dimensional configuration of crustal materials in order to answer these types of questions.

Remote sensing techniques can furnish information about the physical and chemical characteristics of the earth's crust that is directly applicable to such geological questions. For example, aerial photographic measurements have been commonly used in the past to determine the size, shape, and location of surface landforms and the areal distribution of surface vegetation. Airborne radar imaging surveys have also been conducted to determine crustal morphology in areas that are densely vegetated or extensively cloud covered. More recently, experimental spectral techniques have been employed to detect areal variations in the iron and silica content of exposed crustal materials. In addition to electromagnetic remote sensing methods, exploration geophysicists have traditionally used

magnetic and gravity field measurements to investigate the subsurface configuration of crustal materials. A primary goal of the Program is to develop techniques such as these for use in space for the purpose of evaluating the structure and composition of the earth's crust on a global basis.

The development of geological remote sensing methods for use on a global basis is fundamentally dependent upon: (i) a scientific understanding of the phenomenology of remote sensing measurements, and (ii) the ability to construct remote sensing instruments that can operate with the necessary sensitivity and resolution at orbital altitudes. The basic scientific questions involved the development of remote sensing techniques are: How is electromagnetic radiation reflected, absorbed, and emitted at the earth's surface? How is electromagnetic radiation transmitted through the earth's atmosphere? What is the relationship between spatial variations in crustal structure and composition, and spatial variations in the strength and orientation of potential fields observed at spacecraft altitudes?

Knowledge concerning these types of questions is required in order to intelligently interpret remote sensing data and to understand what a particular measurement implies about the physical properties of the earth. Knowledge of this nature is also needed in order to establish technical requirements for the design of future remote sensing instruments. The Program recognizes the equally important roles of applied scientific research dealing with the types of questions listed above and technical research concerned with instrument fabrication in developing geological remote sensing tools for use in space.

3.2 Improve current understanding of the structure, composition, and evolution of the Earth's crust to develop better geological models for global non-renewable resource investigations

The development of a set of technically sophisticated tools for use in space will not necessarily improve the effectiveness of resource exploration activities. Space measurement techniques can supply geologists with various types of information concerning crustal composition and structure. However, this information must ultimately be interpreted in order to apply the individual measurement techniques to specific geological problems.

Geological models form the conceptual basis for the interpretation of information derived from different

types of measurement techniques. As discussed in Section 1, geological models play an important role in mineral assessment and exploration. Geologists routinely use models of tectonic, erosional, and sedimentary processes in performing photogeological studies leading to the preparation of a regional scale geological map. Geological models also describe tectonic settings that favor mineral emplacement, and geochemical patterns at the earth's surface that are indicative of subsurface mineralization. Exploration geologists employ mineralization models in conjunction with regional scale maps to target specific areas for detailed field investigation. Mineralization models continue to be used as field results become available to evaluate the prospects of encountering an economically valuable deposit within a particular area.

Models of crustal mineralization describe phenomena that occur at a variety of scales, ranging from molecular diffusion processes responsible for mobilizing and concentrating certain elements within the crust to plate tectonic processes responsible for the formation and growth of continental landmasses. Small scale geological processes are investigated using a variety of techniques such as detailed field mapping, sophisticated sample analysis methods, and laboratory high pressure/temperature experimentation. Large scale phenomena have traditionally been studied by regional geological mapping studies and regional geophysical survey methods (e.g. aircraft magnetometer measurements and ground based seismic refraction profiling). Global and continental scale processes have largely been investigated by combining and correlating regional geological/geophysical investigations.

Major scientific questions related to crustal mineralization remain to be answered, such as: How did continental landmasses originally form, and how did they grow over the course of geological time? How far backwards in time can currently observed plate tectonic processes be extrapolated? What is the fracture history of the crust, and what effect do deep seated fractures have upon crust-mantle exchange processes and mineral emplacement? What role have volcanic processes played in crustal differentiation and mineral emplacement over the course of geological time?

Knowledge of the processes that have shaped the crust and the sequence in which these processes operated is fundamentally important in searching for mineral resources. Space methods can significantly contribute

to improved understanding of crustal geology, particularly when they are used in conjunction with conventional techniques. The world-wide, synoptic perspective of space techniques make them especially valuable tools for investigating mineral enrichment processes that operate on global, continental, and provincial scales.

4.0 PROGRAM OBJECTIVES

4.1 Develop optimized space-related methods for evaluating the composition and configuration of the earth's near surface crust on a global basis

The earth's surface is covered by a variety of different materials including rocks, soils, unconsolidated rock weathering products, vegetation, water, and man-made cultural features. Remote sensing instruments generally measure the intensity (and sometimes the direction and polarization) of electromagnetic radiation that has been reflected or emitted from the surface. Analysis of these measurements provides information about the surface composition (e.g. mineralogy, elemental abundance, chlorophyll structure) and bulk physical properties (e.g. thermal inertia, dielectric properties) of cover materials. Information of this nature can be used to discriminate between different classes of cover materials and to differentiate materials within individual cover type classes. For example, remote sensing techniques can be used to identify areas where rock formations are exposed at the ground surface, and to differentiate individual formations on the basis of mineralogy and chemical composition.

In order to detect and discriminate cover materials on the basis of remote sensing measurements, prior knowledge of their spectroradiometric characteristics is required. These characteristics need to be determined under laboratory conditions in a controlled environment to better understand the fundamental physical processes involved in the reflection and emittance of electromagnetic radiation. These characteristics must also be determined under field conditions in order to better understand the effects of natural factors such as ground moisture, surface biology, and atmospheric scattering and absorption upon electromagnetic radiation emanating from the earth's surface.

Laboratory and field experiments have demonstrated that the spectroradiometric characteristics of rock materials are directly related to the atomic structure of the rock's component minerals. Experimental studies have been performed in the past in the visible, near, and mid-infrared portions of the electromagnetic spectrum. These studies indicate that certain minerals possess distinctive spectral characteristics, consisting primarily of narrow absorption features (0.05 μ m) at spectral reflectance wavelengths (0.4-2.5 μ m region) and broader emission features (0.5 μ m or greater) at infrared wavelengths (beyond 2.5 μ m). Of particular

importance for resource exploration are the clay and hydrous mineral phases which are ubiquitous at the earth's surface. Previous laboratory studies suggest that various clay and hydrous minerals may be differentiated on the basis of their spectral signatures. However, additional research is needed to determine the position and width of wavelength bands that are optimized for purposes of geologic mapping. This information can potentially be used to design future spaceborne remote sensing systems provided that: (i) high spectral resolution measurements can be performed at spacecraft altitudes, and (ii) extraneous spectral effects introduced by soil moisture, vegetation, and the atmosphere could be accounted for in orbital measurements.

Recent work in the area of radar imaging has suggested that the backscattering characteristics of surficial materials may also be useful for purposes of cover type discrimination and rock type differentiation. Aircraft radar experiments have indicated that multifrequency/multipolarization imaging techniques can detect subtle variations in the roughness of surface cover materials. Further research is needed to develop a theoretical understanding of the manner in which radar pulses are scattered and reflected by surficial materials, and to determine the effects of ground moisture and surface vegetation upon incident microwave radiation. Specification of optimum frequencies and polarizations for geological applications must await this future research.

A major portion of the earth's land surface is covered with vegetation. Consequently, the spectral signature of plant species commonly dominates remote sensing measurements. Past research has demonstrated that in certain instances the distribution, morphology, and composition of plant species is correlated with the composition of underlying rock materials. However, the use of so-called geobotanical methods in mineral exploration is at a relatively primitive stage of development because of the complex interrelationships between vegetative growth and environmental conditions.

The germination and growth of plant species is principally dependent upon groundwater chemistry and availability, and local climatic conditions. Earlier studies have shown that the physical and chemical properties of plants may be altered or subtly modified by metallic elements derived from nearby mineral deposits. Groundwater circulation leaches metallic elements from subsurface and near surface mineral

deposits. These elements are commonly concentrated within groundwater solutions and transported into the root systems of plants and trees. Groundwater containing significant concentrations of metallic elements may stimulate or inhibit a plant's growth, or it may alter the structure of chlorophyll within a plant's leaves. Changes in plant morphology or chlorophyll structure can produce distinctive changes in the spectral characteristics of different plant species.

Further research is needed to understand the physiological basis of observed geobotanical phenomena. Knowledge about the processes that control these phenomena will enable geologists to detect variations in crustal composition within heavily vegetated regions on the basis of remote sensing measurements.

Regional topographic variations have a major influence upon the surface exposure of crustal rock formations. Knowledge of the shape, size, and relief of surface landforms is required in order to infer the thickness, orientation and attitude of individual rock units. Geomorphological analysis also plays an important role in interpreting the tectonic history of a particular region. In many cases the spatial arrangement of surficial landforms is strongly influenced by structural features within the crust such as faults and folds. Quantitative analysis of landform distributions and lineament patterns can be used to infer regional stress directions which may have influenced the emplacement of specific mineral resources.

Topographic information permits geologists to extrapolate knowledge about the surficial distribution of rock materials beneath the ground surface. Consequently, topographic analysis is an important tool in evaluating the subsurface configuration of crustal materials. Standard procedures have been developed in the past for determining relative variations in surface topography through analysis of stereoscopic imagery. Stereoscopic imaging performed at visible, and near-infrared wavelengths is dependent upon natural solar radiation to differentially illuminate the earth's surface. These methods are limited by cloud cover, perennial shadowing (particularly at high latitudes), and diurnal/seasonal restrictions in illumination conditions (e.g., predominance of large sun elevation angles at low latitudes). Stereoscopic imaging can also be performed at microwave wavelengths employing synthetic aperture radars to differentially illuminate the earth's surface. Radar methods are advantageous in that they can be used to image the surface under adverse weather conditions.

They can also be used to illuminate the surface at a wide variety of azimuthal directions and elevation angles. Radar stereoscopic imaging techniques are being experimentally developed at the present time.

Information about the subsurface configuration of crustal materials derived from analysis of stereoscopic data can be augmented and greatly extended through the analysis of potential field measurements. Variations in the strength of the earth's gravity and magnetic fields are related to variations in the composition, density, and structure of subsurface rock materials. Large scale variations in the earth's potential fields can be correlated with major discontinuities in crustal thickness and thermal structure. Potential field measurement techniques represent powerful tools for examining spatial variations in crustal structure and composition in three dimensions.

The development of electromagnetic remote sensing and potential field measurement techniques will be pursued in a parallel manner. The program intends to perform applied research of a scientific nature within individual technique areas to better understand the types of geologically useful information that can be derived from analysis of remotely sensed data. At the same time, the program will conduct technical research to improve the technical capabilities of remote sensing systems.

4.2

Develop improved geological models for global non-renewable resource investigations using space-acquired data

Minerals of economic significance are concentrated within specific portions of the earth's crust by a variety of physical processes which operate over a wide range of spatial scales. At the molecular level, chemical reactions occur that lead to the formation of particular types of mineral phases. For example, metallic ions may be incorporated into groundwater solutions by leaching reactions, and subsequently precipitated due to changes in groundwater chemistry or environmental temperature-pressure conditions. Similarly, in the case of hydrocarbon mineralization, organic material must be heated at moderately high temperatures over relatively long periods of time to form petroleum and/or natural gas. As these examples illustrate, molecular scale processes are strongly influenced by ambient environmental conditions. These conditions are, in turn, governed by geological phenomena operating at larger, regional scales.

Regional tectonic and volcanic processes play a major role in the formation of mineral deposits. For example, tectonic deformation can fracture crustal rocks, producing natural conduits for the subsurface circulation of groundwater fluids. Hydrothermally emplaced deposits, which form due to chemical precipitation from aqueous solutions, may occur as a series of tightly spaced mineral veins deposited along pre-existing fractures. Consequently, tectonic deformation can influence both the occurrence and overall shape of specific types of deposits. Genetic mineral processes may also be affected by regional volcanic activity. The subsurface intrusion of volcanic magma may provide the necessary thermal energy to drive groundwater circulation systems, or to convert buried organic material into crude petroleum.

Regional scale geological processes which affect crustal mineralization are themselves influenced by processes operating at even larger scales. For example, several structural lineaments have been tentatively identified in North America which appear to stretch semi-continuously over distances of several hundreds of kilometers. (Linear structural features with similar dimensions have been observed on several of the other terrestrial planets.) The genesis of large scale crustal lineaments is unknown. They may be the surface expression of deep seated fractures within underlying basement materials, or they may simply result from the fortuitous alignment of shorter structural discontinuities within the near surface crust. Large scale lineaments may have economic significance in that certain mineral deposits appear to be concentrated along such lineaments or at lineament intersections.

Finally, geological processes operating within crustal provinces or continental landmasses are influenced by tectonic and volcanic mechanisms that occur on a global scale. Empirical studies have indicated that certain types of mineral deposits occur in particular geological settings throughout the world. For example, copper porphyry deposits are commonly associated with convergent plate boundaries, such as the western margins of North and South America; whereas lead-zinc deposits frequently occur in intra-cratonic areas, such as the Mississippi River Valley in central North America. These types of associations are thought to be due to global plate tectonic processes. However, the physical mechanisms that give rise to such associations are not well understood at the present time.

Detailed field investigations in regions of known mineralization have permitted geologists to develop

rather sophisticated models of genetic processes that operate at molecular and local scales. These models are based upon voluminous amounts of geological data derived from analysis of rock and soil samples, field mapping, seismic refraction and reflection surveys, magnetic and gravity field measurements, core drilling and subsurface mining activities. In contrast, current understanding of large scale processes that influence crustal mineralization is quite rudimentary. Knowledge of genetic mineral processes operating at continental and global scales is largely lacking. Furthermore, much of the basic geological information required to investigate continental and global scale processes does not exist.

Space measurement techniques can make a major contribution towards improved understanding of large scale crustal processes that govern the formation of mineral deposits. Spaceborne remote sensing systems obtain global measurements of crustal characteristics that are ideally suited to synoptic geological studies. Global geological surveys performed at orbital altitudes also provide an important data base for synthesizing and interpreting geological information obtained by conventional methods (e.g., field mapping, sample analysis, geophysical surveys, etc.). Combined analysis of space acquired data and conventional geological measurements can greatly assist geologists in developing large scale models of crustal structure and composition. Models of this nature will extend our current understanding of the geological history of the earth's crust. They will also help close the gap between detailed knowledge of localized geological phenomena and generalized understanding of global scale processes that govern crustal mineralization.

The Program will sponsor traditional ground based geological investigations such as field mapping and sample studies that directly support the analysis and interpretation of space acquired data. However, the primary thrust of the Program in the area of model development will be to employ space measurement techniques in novel and innovative ways to study crustal structure and evolution at provincial, continental, and global scales.

4.3 Develop space technology and methods to support the evaluation of non-renewable resources on a global basis

Information concerning the global distribution of non-renewable resources is developed on the basis of:
 (i) knowledge of the location, size, and nature of previously discovered deposits, (ii) geological

information about the regional composition and configuration of crustal materials, and (iii) predictive geological models which relate the occurrence of mineralization to specific geologic settings. Global resource evaluation is hindered by the lack of pertinent information on mineral reserves and crustal characteristics for many areas of the world. Furthermore, existing information which is currently available for many areas varies greatly in quantity and quality. Differences in the accuracies, scales, and formats of existing information also hinder global resource analysis.

Geological models which have been employed in past resource assessment studies are limited in several respects which restrict their global applicability. Many models are based upon detailed analysis of several known deposits which may not be generally representative of a specific class of deposits. In addition, earlier work has concentrated upon the local and regional environments in which mineral deposits occur. Models of crustal enrichment processes operating at provincial and continental scales are at a much more primitive stage of development.

Space technology can be used to improve the effectiveness of global resource assessment surveys in several different ways. Space technology permits global surveys of the earth to be conducted in an expeditious manner. Globally acquired space data can be rapidly analyzed to develop geological information concerning the composition, distribution, and structure of crustal materials. This information can be directly applied to evaluation of resource potential. It can also be used to improve and refine geological models employed in assessment investigations.

Geological information derived from analysis of space acquired data is synoptic in scale and comprehensive in nature. It is extremely useful in synthesizing and interpreting information obtained by conventional ground-based and airborne techniques. Space techniques will not replace current methods of resource evaluation. However, space methods involving the combined analysis of space data and conventional measurements can improve both the accuracy and comprehensiveness of global resource assessment studies. The Program seeks to experimentally apply space techniques to practical problems encountered in resource assessment in cooperation with other federal agencies. Experimental research and development will be directed towards improving current methods of determining the global distribution of non-renewable resources.

4.4

Promote understanding of the use of space technology for non-renewable resource investigations by industry, government and academic

At the present time there is an acute lack of geoscientists trained in the proper use of remote sensing techniques. The community of geoscientists with prior experience in remote sensing is quite small. Furthermore, remote sensing practitioners tend to work within specific technique areas. Very few individuals have had experience in the use of different types of remote sensing methods. So, for example, an individual with training in radar imagery analysis is unlikely to have experience in spectral reflectance methods, even though both techniques are potentially useful for geologic mapping.

Remote sensing techniques and associated data analysis methods are currently in an experimental stage of development. The technical capabilities of remote sensing systems are advancing steadily, while the application of previously acquired data to geological investigations has not been fully explored. The failure to fully exploit previously acquired data stems in part from the lack of a user oriented data dissemination system. Experimental data obtained by aircraft and spacecraft systems in the past has been archived in a variety of different institutions, and catalogued using a variety of different procedures. Geological users have been repeatedly frustrated in trying to gain access to experimental data which is potentially applicable to practical and/or scientific investigations.

Under these circumstances, it is difficult for remote sensing practitioners to remain fully abreast of the state-of-the-art. This problem is compounded by the fact that there are very few professional forums where the results of current research in geological remote sensing can be presented. Research is currently being conducted within both private industry and academia. However, communication between these two communities of investigators is quite limited at the present time.

The Program recognizes the need to: (i) train individuals in the proper use of geological remote sensing techniques, (ii) provide necessary resources to the community of geoscientists that represent potential users of experimental remote sensing data, and (iii) increase communication between remote sensing practitioners in industry, government and academia. Towards these ends the Program plans to: (i) create centers of excellence for research and instruction in

the application of remote sensing techniques to non-renewable resource investigations, (ii) establish data bases and a data network by which users can identify and obtain previously acquired remote sensing data, and (iii) organize and sponsor a series of workshops and conferences on the application of remote sensing methods to non-renewable resource studies involving representatives of industry, government, and academia.

5.0 PROGRAM ORGANIZATION

5.1 PROGRAM ELEMENTS

The Non-Renewable Resources Program is comprised of three major elements: (i) an applied research and data analysis program, (ii) a series of Shuttle flight programs, and (iii) a series of free flyer satellite missions. The nature and scope of these program elements are described in this subsection.

Applied research and data analysis (ARDA) projects are concerned with the development and application of geological remote sensing techniques. Applied scientific research is conducted to : (i) investigate the fundamental physical properties of rocks, soils, and other types of surficial material, (ii) determine the manner in which electromagnetic radiation is reflected and emitted from the earth's surface and transmitted through the atmosphere, and (iii) identify crustal phenomena that produce spatial variations in the strength and orientation of the earth's gravity and magnetic fields. Applied technical research is performed to improve the precision, accuracy, and resolution of remote sensing instrumentation. Applied research sponsored by the Non-Renewable Resources Program is directed towards establishing a scientific basis for the analysis and interpretation of remote sensing data, and towards designing future spaceborne remote sensing systems.

Data analysis activities sponsored by the Program employ remote sensing techniques in a novel or innovative fashion to investigate questions of practical value and basic scientific interest related to non-renewable resources. Data analysis activities are principally directed towards: (i) developing improved methods of resource assessment, exploration and development using space techniques, and (ii) improving current understanding of crustal structure, composition, and evolution as it relates to mineralization. All data analysis activities sponsored by the Program are of an experimental nature. In some cases, data analysis projects serve to demonstrate the utility of remote sensing techniques for specific geological applications, such as resource assessment and crustal modelling. In other cases, these projects are used to evaluate the utility of currently available remote sensing systems for specific resource related investigations.

Space shuttle flight programs consist of one or more shuttle orbiter flights dedicated in whole or in part to

the collection of remote sensing data for non-renewable resources applications. In the immediate future the Program will primarily use the Shuttle as an experimental platform to test new instrumentation and to perform proof-of-concept studies of spaceborne remote sensing systems. Over the long term, the Shuttle will also be used as an operational platform to collect certain types of remote sensing data on an intermittent basis as required. Payload development activities which precede a Shuttle flight involve instrument fabrication, space hardening tests, and the construction of accessory equipment required to operate the instrument onboard the Shuttle.

Free flyer satellite missions consist of unmanned orbital platforms dedicated to the operation of a specific collection of remote sensing systems. Free flyer satellites will be developed by NASA solely for experimental R&D purposes. The National Oceanic and Atmospheric Administration currently has responsibility for the development of all operational satellite systems. Free flyer missions are required for certain types of remote sensing survey programs due to limitations in Shuttle orbital characteristics, payload weight, and mission duration. Free flyers missions also prove to be more cost effective than Shuttle flights in certain instances due to the scheduling and duration of Shuttle flights, and the orbital or power requirements of particular remote sensing systems.

5.2 ARDA Subprogram Elements

Applied research and data analysis (ARDA) activities form the core of the overall Non-Renewable Resources Program. Shuttle payload programs and satellite free flyer missions are designed to support the technique development and application activities conducted within the ARDA program. New initiatives in the shuttle payload and free flyer programs are justified on the basis of the results of ARDA investigations.

ARDA encompasses a wide variety of activities. These activities are classified into four major subprogram elements discussed in this subsection. Each element of the ARDA program is described below, and major programmatic thrusts in the near term are presented. Implementation plans for various elements are being developed at specific NASA field centers.

5.2.1 Geologic Mapping Techniques

This subprogram element is devoted to developing remote sensing techniques which can be used to detect spatial

variations in the composition, mineralogy, structure, and distribution of crustal materials. Technique development research is currently being performed throughout the useful portions of the electromagnetic spectrum (visible, near and mid-infrared, and microwave wavelengths). Parallel development of potential field measurement techniques is also being conducted. Extensive research is required to determine the types of geological information that can be derived from analysis of remote sensing measurements. This research is directed towards employing remote sensing methods for purposes of rock type discrimination, geobotanical mapping, topographic analysis, and subsurface crustal analysis (see Fig. 1). Geological information of this nature is directly applicable to geological mapping.

The development of remote sensing techniques for geological mapping is being pursued in two different fashions. Integrated programs of research are developed within individual technique areas to determine the capabilities and limitations of specific measurement methods. These integrated research programs involve laboratory measurements, in situ field measurements, development of aircraft instrumentation for test site investigations, and theoretical modeling. The relative importance of these activities varies from one technique area to the next, depending upon the technical maturity and state-of-the-art capabilities within each area. In general, the emphasis shifts from laboratory and ground based field studies to test site investigations and orbital experimentation as development progresses. However, it is important to realize that technique development is an inherently iterative process, in which applied scientific research leads to instrument development, and instrument experimentation creates a need for additional scientific research.

In addition to organizing integrated research programs within individual technique areas, the Program also sponsors major test case projects in which a variety of different techniques are experimentally used to geologically map a specific area. Test case projects are designed to evaluate the utility of multiple remote sensing techniques for geological mapping in specific environments. The major test case project conducted in the past was organized in cooperation with private mineral/hydrocarbon companies that belong to the Geosat Committee. Under the auspices of this project NASA obtained remote sensing data over a series of test sites within regions of known mineralization. The Geosat companies provided detailed ground truth data in the test site areas based upon prior mapping, sample

analysis, and geophysical surveys. Analysis of the data is being conducted jointly by NASA scientists and researchers from private industry.

Future plans call for the reorganization and expansion of the NASA/Geosat Test Case Project. In addition, a Geobotanical Test Case Project is being organized along similar lines to apply remote sensing techniques to geological mapping in vegetated regions.

5.2.2 Geological Model Development

This subprogram element is devoted to applying remote sensing techniques to the study of the composition, structure, and evolution of the earth's crust. Basic crustal research sponsored by the Program seeks to relate the occurrence of mineral deposits to large scale variations in crustal structure and composition. Primary emphasis is upon the development of crustal models at global, continental, and provincial scales. Basic crustal research leads to the development of mineral occurrence and genesis models which are used routinely in resource assessment and exploration.

The major thrust is in this area over the near term will be upon consortium studies of mineralized crustal features. These consortium projects will be conducted by multidisciplinary groups of scientific investigators. The projects will develop crustal models through combined analysis of electromagnetic remote sensing data, potential field measurement, and geological information derived from conventional techniques. A series of workshops and conferences will be sponsored by the Program to focus on the attention of the scientific community at-large upon the usefulness of remote sensing methods for the analysis of large scale crustal features. In addition, geological and geophysical data bases will be established in the future to support global studies of crustal structure, composition and evolution.

5.2.3 Global Resource Evaluation Methods

This subprogram element is devoted to applying remote sensing techniques to resource assessment problems in order to develop improved methods of estimating the global distribution of non-renewable resources. NASA's efforts in applying remote sensing techniques to global resource evaluation will concentrate strictly upon experimental research and the development of experimental methods. Primary responsibility for mineral/hydrocarbon assessment on a global scale resides

within the U.S. Departments of Interior and Energy. NASA Headquarters is in the process of formulating an interagency steering group composed of representatives of these Departments and the National Science Foundation to develop a coordinated interagency program in global resource evaluation.

A series of interagency workshops and topical conferences will be held in the immediate future to (i) evaluate the current state-of-the-art of global resource assessment methods, (ii) explicitly define assessment models in current use (iii) identify the types of geological information employed in resource assessment, and (iv) determine the potential role of space remote sensing techniques in evaluating resource potential on a global basis. These workshops will lead to the subsequent initiation of an assessment test project employing space techniques to be conducted somewhere within the continental U.S. This test project will be conducted in cooperation with other government agencies. It will be designed to evaluate the potential usefulness of space techniques for mineral/hydrocarbon appraisal on a global basis. The continental U.S. test project could conceivably lead to the development of a pilot program of global resource evaluation employing space technology.

5.2.4 Centers of Excellence

This program element is devoted to the development of institutions which can formulate and maintain high caliber programs of research and instruction in the application of space techniques to non-renewable resource investigations. The objectives of the centers of excellence program are threefold: (i) to train geoscientists in the proper use of remote sensing techniques; (ii) to provide research facilities, resources, and continuing education for remote sensing practitioners in industry and academia, and (iii) to serve as an institutional interface between the various user groups involved in the Non-Renewable Resources Program.

Centers of excellence will initially be established in proximity to major NASA field centers. Centers of excellence will be allied with academic institutions in the local and regional area. They will also develop associations with nearby industrial/academic research facilities. Centers of excellence will foster closer working relationships between NASA, industry and academia through a variety of activities, such as:

- (i) **Data Users Services** - providing users with information about obtaining previously acquired data, possibly offering a limited selection of standard data products for public sale
- (ii) **Geological/Geophysical Data Bases** - establishing collections of space data in image and digital format to support global studies of crustal structure and composition
- (iii) **Graduate and Post-Doctoral Residence Programs** - permitting graduate students and post-doctoral candidates from various academic institutions to conduct research over extended periods of time
- (iv) **NASA/Geosat Associates Program** - enabling NASA scientists and industrial researchers to work and teach at the center
- (v) **Continuing Education Programs** - consisting of lectures, seminars, and short courses that would enable remote sensing practitioners in industry and academia to remain abreast of state-of-the-art advances in remote sensing technology and applications.

During the next decade several centers of excellence will be developed throughout the country. Each center will have a somewhat different orientation, and each will focus upon some particular aspect of the overall Non-Renewable Resources Program. Current plans call for the first center to be developed in the Houston, Texas area in proximity to the Johnson Space Center. The second center of excellence will be established in proximity to the Goddard Space Flight Center in Greenbelt, Maryland.

APPENDIX I

CURRENT STATUS OF GEOLOGICAL REMOTE SENSING TECHNIQUES

The measurement capabilities of remote sensing systems currently employed for geological applications was reviewed as a part of this study project. The results of this review are summarized in both tabular and graphical formats in this appendix.

Table I-1. This table summarizes instrument systems and associated data sets that are in routine use, under development, and under study within individual technique areas.

Table I-2. This table summarizes the maximum spectral and spatial resolution of remote sensing systems which are currently being operated on a routine basis at aerial and orbital altitudes.

Figure I-1. This figure describes the spectral and spatial resolution of spaceborne sensor systems deployed in the past. The spectral position and width of measurement bandpasses are represented by horizontal bars, the ground resolution of these systems is given in parentheses.

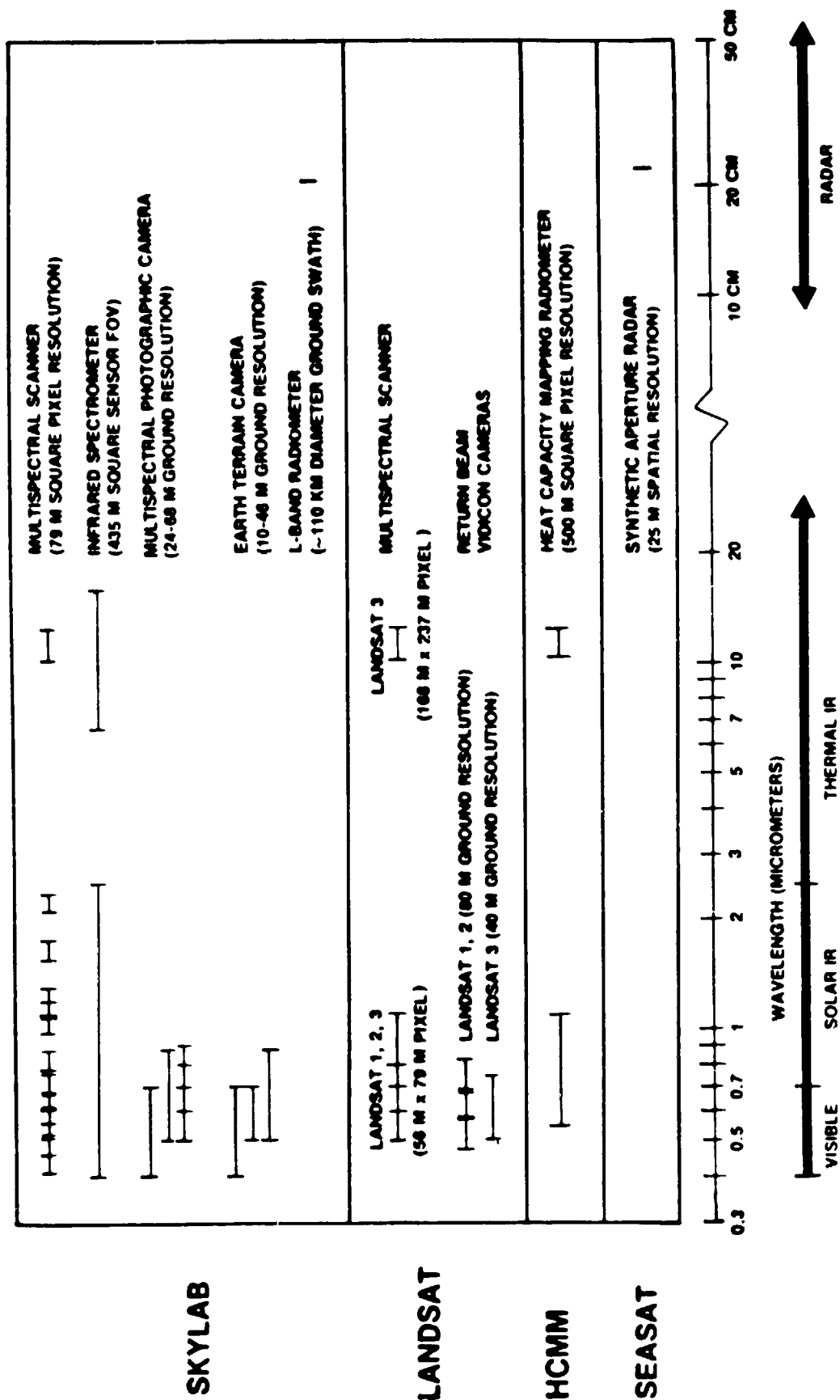


Figure I-1

GEOLOGICAL REMOTE SENSING RESEARCH PROGRAM

CURRENT STATUS OF MEASUREMENT TECHNIQUES

	ELECTROMAGNETIC REMOTE SENSING				POTENTIAL FIELD MEASUREMENT	
	VISIBLE / NEAR IR	THERMAL IR	MICROWAVE	MAGNETIC FIELD	GRAVITY FIELD	
IN ROUTINE USE	GEMINI/APOLLO/ SKYLAB PHOTOGRAPHY LANDSAT (MSS, RBV) AIRCRAFT SCANNERS	HEAT CAPACITY MAPPING MISSION (HCMM) AIRCRAFT SCANNERS	SEASAT SAR AIRCRAFT SAR SYSTEMS (X, C, L-BAND)	POLAR ORBITING GEOPHYSICAL OBSERVATORY (POGO 2, 4, 6) MAGSAT	SATELLITE TRACKING GEOS-3 SEASAT ALTIMETER	
IN DEVELOPMENT	LANDSAT (THEMATIC MAPPER) SHUTTLE MULTISPECTRAL INFRARED RADIOMETER (SMIRI) LARGE FORMAT CAMERA (LFC) MULTISPECTRAL LINEAR ARRAY SCANNERS	6-CHANNEL AIRCRAFT SCANNER	SHUTTLE IMAGING RADAR-A (SIR-A)			
UNDER STUDY	SHUTTLE STEREO IMAGER PASSIVE FLUORIMETRY	SHUTTLE MULTIBAND THERMAL IMAGER MULTISPECTRAL LINEAR ARRAY SCANNERS	SIREX • VARIABLE ANTENNA • DEPRESSION ANGLE • MULTIFREQUENCY • MULTIPOLARIZATION	TETHERED MAGNETOMETER MAGSAT-B	GRAVSAT GRAVITY GRADIOMETER TOPEX	

Table I-1

REMOTE SENSING TECHNIQUES

— CURRENT MEASUREMENT CAPABILITIES

		AIRCRAFT	SPACECRAFT
ELECTROMAGNETIC	VISIBLE/ NEAR IR	0.03 μ m BANDWIDTH 5 m GROUND RESOLUTION	0.1 μ m BANDWIDTH 56 m GROUND RESOLUTION
	THERMAL IR	0.5 μ m BANDWIDTH 10 m GROUND RESOLUTION	2 μ m BANDWIDTH 600 m GROUND RESOLUTION
	MICROWAVE	MULTIFREQUENCY X, C, L, BAND MULTIPOLARIZATION HH, HV, VH, VV 5 M GROUND RESOLUTION	SINGLE FREQUENCY L-BAND SINGLE POLARIZATION HH 25 m GROUND RESOLUTION
POTENTIAL FIELD	MAGNETIC FIELD	0.1 GAMMA 10 m GROUND RESOLUTION	6 GAMMA ANOMALIES OVER 300 Km DISTANCE
	GRAVITY FIELD	NONE	VARIABLE 10 MILLIGAL ANOMALIES OVER 100 Km DISTANCE (OCEANS)

Table I-2